TWO-DIMENSIONAL AND NUMERICAL ANALYSIS OF SIALON-BASED CUTTING TIPS THERMAL CONDUCTIVITY BY USING SEM IMAGES

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ABSTRACT
In this study, two-dimensional and numerical solution of sialon-based cutting tips’ thermal conductivity was done by using SEM images. Finite element solutions were repeated for different area ratios and node amounts. Area ratios and node amounts changed according to the structure of finite element model. While sintering the materials, grain boundary phase called as “interphase” occurred beside the main phase structure. This structure was made out in the electron microscope (SEM) images of material and in the models of numerical analysis. While doing the numerical analysis, effective thermal conductivity was computed by a finite material based program (Ansys) depending on knowing the conductivity of main phase and interphase by considering SEM images as a two-dimensional surface. The calculations were given as comparative to the analytical and experimental results. When the results are compared, it is proved that thermal conductivity of cutting tips or the similar materials with two-phase structures can be set down by numerical calculations beside their analytical and experimental measurements.

Keywords: Thermal Conductivity, Sialon, Cutting Tip, SEM
Nomenclatures

A  Area (m$^2$)
L  Length (m)
k  Thermal Conductivity (W/m.K)
ke  Effective Thermal Conductivity (W/m.K)
kf  Thermal Conductivity of Main Phase Material (W/m.K)
km  Thermal Conductivity of Inter Phase Material (W/m.K)
φ  Volumetric Rate
T  Temperature (K, °C)
$k_x,k_y$  Thermal Conductivity depend on dimension (W/m.K)
α  Thermal Diffusivity Coefficient (m$^2$/s)
ρ  Density (kg/m$^3$)
q  Heat Flux (W/m$^2$)
γ  Enlargement Element (Enlargement ratio/50,000)
q  Thermal Power (W)
c  Specific Heat (J/kg.K)
v  Volume (m$^3$)
(x,y)  Coordinate axis

1. INTRODUCTION

Today the cutting speed for the cutters used in manufacturing has constituted high temperatures between the cutter and the rake face. This situation features the usage of materials including good mechanical characteristics on high temperatures. When the resistance of enduring to high temperatures is considered, ceramics have shown better performance. Ceramic cutting tips with high rigidity characteristic can protect their rigidity on high temperatures and don’t react with the work piece. Their endurance life to high cutting speeds is high. α-Sialon ceramics have shown high rigidity, high fracture toughness, high resistance, high chemical resistance and high wear resistance. As sialon ceramics can be used without lubricant in contact with the metallic pieces and are durable on high temperatures, they are indispensable on corrosive environments in manufacturing industry.

The studies based on Rayleigh and Maxwell’s [1] researches for determining the thermal conductivity of composites has revealed a lot of models until now. A lot of analytical, experimental and numerical studies were made on this subject [2,3]. The studies in literature are usually experimental and were used for determining the thermal conductivity of the materials [4,5,6]. The chemical behaviours and internal structures of composites and especially advanced engineering ceramics in high temperatures were searched by using scanning electron microscope [7]. The changes occurring in chemical structure and the structural problems were searched [13,15]. Numerical solutions were made by using finite difference method for some materials [16,26].

In this study, the thermal conductivity was calculated analytically, numerically and experimentally and the results were compared. SEM images obtained by electron microscope were modelled by a program based on finite element, two different materials were identified for main phase and interphase and the thermal conductivity value was used differently. As a result, effective thermal conductivity was calculated for the whole composite. The thermal change of main phase material was considered in numerical solutions.
In the numerical study, constant surface heat was used with the help of SEM images, and effective thermal value was found by calculating the heat flux in the boundaries. The thermal conductivity was calculated two dimensional depending on the temperature, but in the literature, two dimensional analyses depending on the temperature weren’t observed.

The experimental studies were made by using the Laser flash technology in laboratory. Specific heat, intensity and thermal diffusion coefficients of the samples were calculated and thermal conductivity was identified by using \( k = \alpha \rho c \) formula.

Analytical studies were made for comparing the numerical results. These analytical solutions were made by the empirical terms used in literature. The areal ratios of solution surface from SEM images were identified, and the analytical solutions were compared on the same geometry.

2. MATERIALS AND METHOD

The solutions can be made by considering the systems where the temperature and energy transfer is the function of only one position coordinate. However, in industry and practice, the complex geometry in the composites and the definition type of boundary conditions make essential the usage of two or three-position coordinates. So, in this study, two dimensional solutions for Sialon based ceramic cutting tips were made. When two dimensional solutions of the material were made, the boundary conditions in Figure 1 were used.

The aim of solving any thermal conductivity problem is to determine the heat flux and temperature distribution. Heat flux is calculated on solution surface where constant surface temperature boundary condition is used. The thermal conductivity can be found for \( x \) and \( y \) lines by using the heat fluxes. Effective thermal conductivity depending on the line \( (k_x,k_y) \) has different values. The reason of this is the change of thermal conductivity depending on the line.

\[
\begin{align*}
T (0,y) &= T_{y1} \\
T (L_x,y) &= T_{y2} \\
T (x,0) &= T_{y3} \\
T (x,L_y) &= T_{y4}
\end{align*}
\]

The surface was cauterized with suitable acids for clearer SEM images. The images of main phase and interphase materials are diverged with lines in the Ansys programme. The areas formed by using these lines were shown in Figure 2. These areas can be thought as two different composite with different physical characteristic. The thermal conductivity of these areas and the change functions of them depending on the temperature are identified. So, it is the thermal conductivity problem in two dimensional steady regimes. The numerical solution can be done under the given boundary conditions.

The size of elements or lines forming the areas determines the number of nodal used for the solution. The number of node must be on a level that doesn’t negatively affect the numerical solution on small areas especially on interphase areas. It is clear that the fluid solution of elements will be made more correctly in the inner regions out of the boundaries of interphase forming a resistance to thermal conductivity. Solution surface can be seen in Figure 3.

3. THEORY

In the study, as numerical solutions were made for the situations where the thermal conductivity changed with temperature, this change was given on Table 1. These values were measured in laboratory
environments for Sialon material. Average thermal conductivity value is taken as 10.765W/m.K for the situation where the thermal conductivity didn’t change. While making both solutions, the value of interphase thermal conductivity was taken as 0.65W/mK. The interphase material is a glassy structure composed during the combination of elements in cutting tip. The change of thermal conductivity and heat couldn’t be identified in the studies in literature and laboratory environment. If the volumetric ratio of interphase in ceramic cutting tips is low, grain size on thermal conductivity, thermal conductivity of main phase and structural errors gain importance.

The surface temperatures were identified as respectively 298K, 373K, 473K, ..., 1273K by considering that the temperature differences weren’t low than 100 K in both lines. The isotherms under these temperatures were given in Figure 4 and temperature gradients were given in Figure 5. When the Figure 5 was examined, the relationship between node number on solution surface and effective thermal conductivity coefficient can be determined. \( \gamma \) is identified as growth factor for making it understand easily. \((\gamma=1)\) is for 50000 growth rate, \((\gamma=0.6)\) is for 30000 growth rate and \((\gamma=0.5)\) is for 25000 growth rate.

It is known that effective thermal conductivity of composites is changed depending on the directions. Surface boundary condition on the other direction is used for determining the conductivity in one dimensional heat transfer. While two dimensional solutions were made, constant surface heat boundary condition on two directions was identified. The thermal conductivity for different magnifications was given in Table 2 and Table 3. While the calculations in the Tables were made:

1. When the thermal conductivity of phase material changed with the temperature, values in Table 1 were observed. When the thermal conductivity of phase material became constant, 10.765W/mK value was obtained. In both situations, operation was made by using 0.65W/mK value as the thermal conductivity of interphase material.
2. The node count was identified by doing mesh in Ansys programme.
3. \( T_1=298 \text{ K}, T_2=1273 \text{ K}, T_3=298 \text{ K} \) and \( T_4=1273 \text{ K} \) values were taken as boundary conditions.
4. Heat flux values on \( x=0, x=L_x, y=0 \) and \( y=L_y \) surfaces were calculated from the programme.
5. \( q_{\text{difference}} = (q_x=0) - (q_x=L_x) \) and \( q_{\text{difference},y} = (q_y=0) - (q_y=L_y) \) flux differences were calculated.
6. \( (k_x) \) and \( (k_y) \) were calculated from \( q_{\text{diff,x}} = k_x \frac{\Delta T}{L_x} \) and \( q_{\text{diff,y}} = k_y \frac{\Delta T}{L_y} \) equations.

While determining the effective thermal conductivity of composites in the study, the calculations were made considering two-dimensional heat transfer. When it was considered that the thermal conductivity of main phase material didn’t change parallel to heat, Figure 6 and Figure 7 were obtained; when the thermal conductivity of main phase material changed parallel to heat, Figure 8 and Figure 9 were obtained. In both situations, when the node count passed a certain value, effective thermal conductivity of the composite didn’t change.

Effective thermal conductivity didn’t change after node count passed a certain value and became asymptote in one value. So, the increase of node count is very important on effective thermal conductivity solutions.

For numerical solutions, the situation that main phase thermal characteristic of thermal conductivity changed, and the hypothesis that main phase thermal characteristic was constant were used. The relationship between node count and magnification ratios is an important parameter in solutions and it corresponds to finite element magnitude. Increasing the node counts considering the whole geometry causes much element formation on big areas and a parallel rise on interphase areas. For solving this, interphase and main phase
areas can be divided into different elements and then these areas can be integrated again; as a result it means less node and better results. In this study, considering the magnification ratios, this method wasn’t used. This deficiency is tried to remove by using high element count.

4. RESULTS

When the effective thermal conductivity as an internal structure in Sialon based cutting tips is examined, the effect of interphase element can be understood more clearly. When the amount of interphase with low thermal conductivity value decreases, effective thermal conductivity increases according to the mixture rule.

\[
\text{main phase / interphase} \uparrow \quad \text{conductivity} \uparrow
\]

However, when the interphase amount decreases, effective thermal conductivity doesn’t increase in expected proportion. The reason of this is the grain size magnitude effect of main phase element which is denser volumetrically. When the grain sizes of main phase reduced, effective thermal conductivity will be decreased. The reason of this is that the effect of main phase with increasing grain size to effective thermal conductivity will be more.

\[
\text{Grain size} \uparrow \quad \text{diffusivity} \downarrow
\]

In Figure 12 and 13, the comparison of experimental calculations with results in (x) and (y) directions in different magnitude ratios are given when the thermal conductivity of main phase element changes with temperature. When one and two dimensional solutions are examined, it is observed that if magnitude ratio decreases numerical results approach to experimental ones. If both (x) and (y) directions are considered, the solutions with 25000 magnitude ratio become the most optimal numerical solution. The less magnitude ratios are, the more realistic areas belonging to main phase and interphase will be. However, when the area count increases, the solution in drawing and analysis programmes will be difficult.

When numerical modelling was made for composite, different mesh was made in Ansys programme and solutions were made on different element count. After the element count passed the value of 50000, effective thermal conductivity coefficient didn’t change. The results taken from two dimensional numerical solutions were given in Figure 14. After determining \((k_x)\) and \((k_y)\) values on numerical calculations, effective thermal conductivity was calculated from Equation 1. When the magnitude value was 0.6 as a result of numerical calculations, the values were found approximate to the experimental results.

\[
(k_e)^2 = (k_x)^2 + (k_y)^2
\]  

5. CONCLUSIONS

Two-dimensional and numerical solution of sialon based cutting tips’ thermal conductivity has been done by using SEM images. This structure has been made out in the electron microscope (SEM) images of material and in the models of numerical analysis. While doing numerical analysis, effective thermal conductivity has been computed by a finite material based program (Ansys) depending on knowing the conductivity of main phase and interphase by considering the SEM images as a two-dimensional surface. The calculations were given as comparative to the analytical and experimental results. When the results are compared, it is proved that thermal conductivity of cutting tips or the similar materials with two phase structures can be set down
by numerical calculations beside their analytical and experimental measurements. According to the technique used in the industry, cutting tips are produced first and then thermal conductivity measurements are carried out. In this study, first modelling and calculation of tips’ thermal conductivity and then producing the cutting tips are aimed.

REFERENCES


**TABLES**

Table 1. The change of thermal conductivity and temperature for anaphase material [2].

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>298</th>
<th>373</th>
<th>473</th>
<th>573</th>
<th>673</th>
<th>773</th>
<th>873</th>
<th>973</th>
<th>1073</th>
<th>1273</th>
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Table 2. Boundary conditions and results for two-dimensional (x) line.

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<thead>
<tr>
<th>Magnification ratio</th>
<th>Node count</th>
<th>Lx (mm)</th>
<th>Ly (mm)</th>
<th>T1=T3 (K)</th>
<th>T2=T4 (K)</th>
<th>ΔT (K)</th>
<th>qfx (W/mm²)</th>
<th>kx (W/m.K)</th>
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<td>421.31</td>
<td>294.66</td>
<td>298 K</td>
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<td>975 K</td>
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<td>626.24</td>
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<td>50000</td>
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<td>7.99x10⁻³</td>
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Table 3. Boundary conditions and results for two-dimensional (y) line.

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<th>Node count</th>
<th>Lx (mm)</th>
<th>Ly (mm)</th>
<th>T1=T3 (K)</th>
<th>T2=T4 (K)</th>
<th>ΔT (K)</th>
<th>qfy (W/mm²)</th>
<th>ky (W/m.K)</th>
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<tbody>
<tr>
<td>25000</td>
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<td>12.5x10⁻³</td>
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<tr>
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<td>918.48</td>
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<td>975 K</td>
<td>7.21x10⁻³</td>
<td>6.8</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1: Two-dimensional modeling of SEM image.

Figure 2: The areas formed in Ansys programme.
Figure 3: Image of nodal points.

Figure 4: The temperature distribution results for two-dimensional solutions.
Figure 5: The temperature gradients for the solution in two-dimensional variable characteristic.

Figure 6: The change of effective thermal conductivity on constant (x) direction.
Figure 7: The change of effective thermal conductivity on constant (y) direction.

Figure 8: The change of effective thermal conductivity on variable (x) direction.
Figure 9: The change of effective thermal conductivity on variable (y) direction.

Figure 10: The change of effective thermal conductivity on two dimensional (x) direction.
Figure. 11. The change of effective thermal conductivity on two dimensional (y) direction.

![Graph showing the change of effective thermal conductivity on two dimensional (y) direction.](image)

Figure. 12: The comparison of results on two-dimensional (x) direction with variable characteristic.

![Graph showing the comparison of results on two-dimensional (x) direction with variable characteristic.](image)
Figure 13: The comparison of results on two dimensional (y) direction with variable characteristic.

Figure 14: The comparison of two-dimensional results.